AGARDograph 63

Radio Navigation Systems

FOR AVIATION AND MARITIME USE

A Comparative Study

Technical Editor

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CONTENTS

2.04. VOR-SYSTEM

The Very High Frequency Omni-directional Range System

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1. GENERAL INTRODUCTION

Omni-directional ranges (Omniranges) operating in the low-frequency band have been known and used since 1908 (Telefunken Kompass[17]). The radio lines of position obtained from such omni-directional ranges can be utilized by simple airborne equipment. With the transition to v.h.f. techniques—in order to overcome interferences by statics and night effect—the v.h.f. omni-directional range (VOR) was developed in the U.S.A. and is still operating on the same principle today, although a variety of different constructions are in use.

The VOR system indicates the magnetic bearing of the omnirange (Fig. 1) to the pilot by means of an omni-bearing indicator. For indication, however, the same meter as for the radio compass, i.e. the radio-magnetic indicator (RMI), may be used as well. On a flight toward or away from the Omnirange the deviation from a line of position selected by means of the omni-bearing selector (OBS)* may be indicated by a deviation indicator (cross-pointer instrument) whose pointer is deflected either to the left or to the right, An additional to/from indicator provided on the omni-bearing selector shows whether the bearing indicated on the omni-bearing selector is measured *from* the VOR to the aircraft or from the aircraft *to* the VOR.

It was originally intended to combine VOR with a DME (Distance Measuring Equipment). Such a navigation system would have enabled the pilot to fix his position by reference to one ground station only. The plans were influenced, however, by the development of the TACAN system, which was intended for military purposes, in such a manner that the DME was disregarded. The TACAN system is similar to the VOR–DME combination. Instead VOR was combined with the TACAN system (cf. Description of Operation, Chapter 2.05). This new system is called the VORTAC system.

Although distance information is not yet provided by the VOR system, some hundred VOR installations are operating in various countries, because, located at or close to the destination, they allow for an easy navigation with the flight following a radial line—course deviations being displayed by a zero indicator (cross-pointer) and the required azimuth being preselected.

The r.f. energy emitted by VOR depends on the application (installation on an airport or along an airway) and varies between 50 and 200 W.

* Often also referred to as " Course Selector " which may give rise to errors.

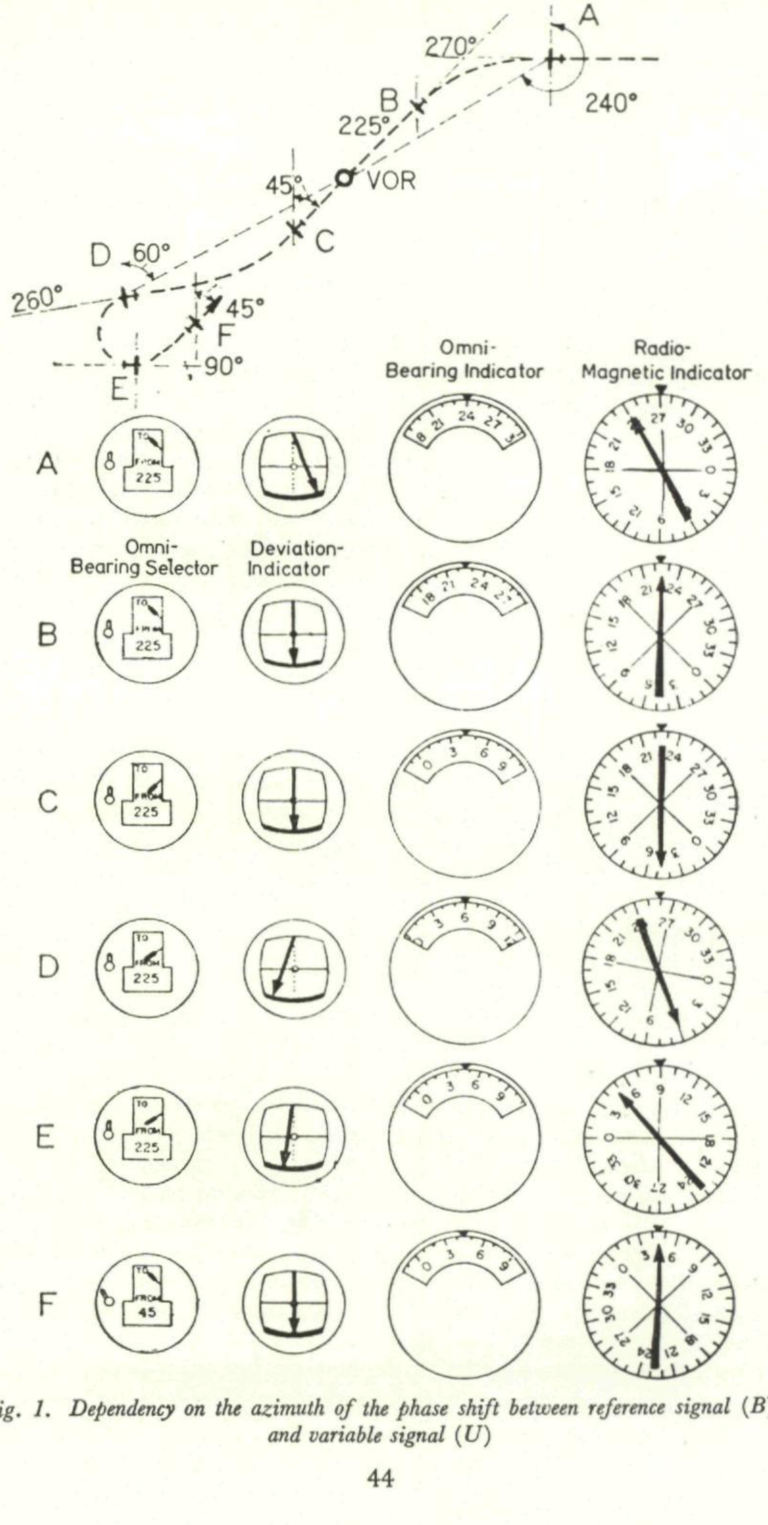

Fig. 1. Dependency on the azimuth of the phase shift between reference signal (B) and variable signal (U)

Constructions differ primarily in the antenna system (cage-type antenna, slotted antenna, Alford antenna array). The coverage obtainable corresponds to the optical line of sight plus allowance for tropospheric refraction. Coverage is therefore dependent upon the altitude of the aircraft.

2. PRINCIPLES OF OPERATION

The principle of the VOR system[1–10] is based on phase comparison between two audio-frequency oscillations of equal frequency (30 c/s) associated with the radio-frequency radiation. In order to separate the two wave-trains of equal frequency in the receiver a special trick is used. The greater portion (approximately 90 per cent) of the r.f. energy generated is emitted by an omni-directional antenna (*B* of Fig. 2) and is amplitude modulated with 10 kc/s (9960 c/s) whereby the sub-carrier in turn is

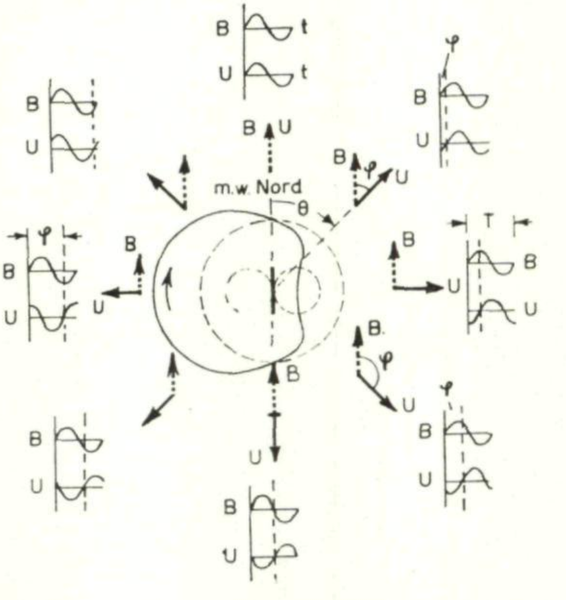

Fig. 2. Airborne instrument indications illustrating a flight path

frequency modulated with 30 c/s (reference phase signal). A small portion (approximately 10 per cent) of the r.f. energy generated, however, is not modulated and is emitted by a directional antenna (figure-of-eight radiation pattern, *U* of Fig. 2). Both partial r.f. fields are phase locked. Since the directional pattern is rotated at a speed of 30 rev/sec, for instance by mechanical rotation of the respective dipole, the field is amplitude modulated at 30 c/s in the point of reception and its phase aspect varies with the bearing of the receiver (variable phase signal) (Fig. 2).

In the aircraft a receiver is used which is applicable to both VOR and ILS. In this unit (see Fig. 3) for VOR reception the 30 c/s signal of the 10 kc/s subcarrier is recovered from the r.f. signal received and, at the same time, the 30 c/s signal of the azimuth-depending amplitude modulation is detected. The phase difference between both signals is presented by

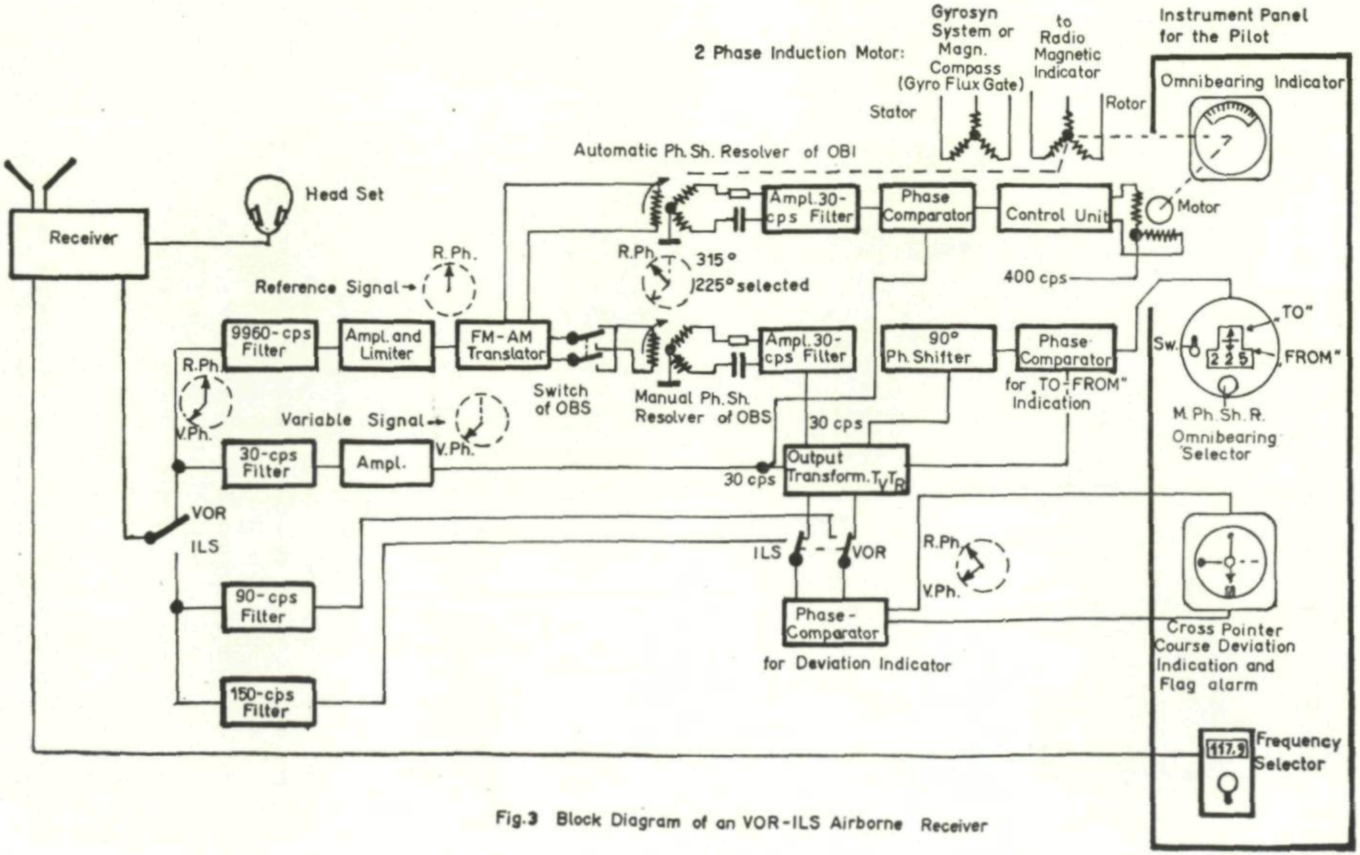

Fig. 3 Block Diagram of an VOR-ILS Airborne Receiver

means of a phase meter and an automatic device on the omni-bearing indicator. If the phase angle is zero with respect to north, the phase angle indicated will be equal to the azimuth.

The automatic device comprises a servo-driven phase selector (automatic resolver) incorporated in the omni-bearing indicator which is coupled to the 360° scale and a control unit (manual resolver) by means of which the servo motor of the omni-bearing indicator is operated until zero is indicated by the phase meter. The omni-bearing indicator then indicates the bearing of the aircraft relative to the VOR station on its 360° scale. For reading, a fixed mark indicating magnetic north is provided at the top of the instrument. A radio-magnetic indicator (RMI) can be connected by means of a synchron motor, whose rotor is also coupled to the omni-bearing indicator servo motor. Thus the position of the radio-magnetic indicator pointer coincides with that of the omni-bearing indicator. In order to obtain coincidence between the radio-magnetic indicator and radio compass indication—the fixed triangular mark on the radio-magnetic indicator must indicate the longitudinal axis of the aircraft and not magnetic north—the angle between magnetic north and VOR station* will have to be corrected by the compass data; it is only then that the azimuth can be read from the 360° scale. For this purpose, the stator system of the synchro motor of the omni-bearing indicator is fed by the synchro generator of a magnetic compass. Thus the zero position of the omni-bearing indicator is changed with the zero position of the magnetic compass (magnetic north). Then the following conditions are indicated by the radio-magnetic indicator: The compass course, i.e. the angle between magnetic north and the longitudinal axis of the aircraft (scale value indicated by the mark, Fig. 1); the magnetic bearing of the VOR (scale value indicated by the pointer); and the angle between the longitudinal axis of the aircraft and the VOR (pointer on mark). When a deviation indicator (cross-pointer instrument) is used, a phase selector incorporated in the omni-bearing selector and a separate phase mater (Fig. 3) are employed.

The phase meter is connected directly with the deviation indicator, which indicates zero (centre position of the pointer) when the phase of the variable signal coincides with the phase of the reference signal which is adjusted by the manually operated phase selector. Since the phase of the variable signal can be shifted over a 360° range, any desired azimuth can be selected.

When the field strength received is too small to secure a reliable operation of the phase meters, the cross-pointer instrument will signal this condition (flag alarm).

An additional phase measuring facility (Fig. 3) compares the angular value received from the VOR with the bearing set manually on the omni-bearing selector. The result of this comparison is indicated on the to/from indicator. It is the purpose of this to/from indicator to show the pilot whether the bearing indication, which is obtained from the deviation indicator together with the value set on the omni-bearing selector, indicates the direction *from* the station to the aircraft, or the direction from the aircraft

* As transmitted from the omni-bearing indicator.

to the station. Since the VOR bearing is independent of the direction of the longitudinal axis of the aircraft (heading) (as contrasted with the bearing taken with direction-finders on board) there is no direct relationship between the to/from indication and the heading. Therefore, the indication remains constant, e.g. from, if a VOR radial is set on the OBS, whether the aircraft is flying towards or away from the station or just passing it. When, however, the correct relationship between omni-bearing indication and heading has been established, which is usually the case when the VOR is used as reference on airways, the to/from indication is valid in the same way for the heading and remains to be correct even when the aircraft has been flown over the station. If, for instance, the indication during approach was *to* it is automatically changed into *from* when the aircraft has been flown over the station, provided the OBS setting remains unchanged.

In order to achieve quickly coincidence of VOR reading and heading, a separate change-over switch is provided by means of which the bearing value can be changed by 180°. The to/from indication is reversed at the same time (cf. Fig. 1).

Doubts as to the existing relationship between heading and bearing can be overcome easily by comparing the bearing indication with the compass indication. If the compass system fails, the relationship between the to/from reading and the heading can also be read from the deflection of the cross-pointer instrument; if the to/from indication coincides with the heading, the pointer of the cross-pointer instrument is deflected to the right if there is a deviation to the left of the intended line of position; pointer deflection is to the left in the case of a left-hand deviation.

The system is to operate in the 108–118 Mc/s frequency band so that 80 channels are available with a channel spacing of 100 kc/s. In the 108–112 Mc/s range only such frequencies are used which correspond to even-numbered multiples of 100 kc/s, e.g. 108.2 Mc/s, 108.4 Mc/s, etc. (i.e. 20 channels); the odd-numbered multiples, e.g. 108.1 Mc/s, 108.3 Mc/s, etc., are reserved for the instrument landing system. In the range of 112–118 Mc/s all frequencies spaced by 100 kc/s are used (60 channels). These channels can be distributed over a sufficiently large area so that interference of VORs operating on the same frequency in adjacent areas will not occur in practice (cf. section 3.3).

3. RANGE AND ACCURACY

3.1. *Range*

The VOR system is a short-range navigation system. The range is dependent upon the altitude of the aircraft. It is equal to the range of very high frequencies (optical sight) plus approximately 15–20 per cent. Thus the following ranges are obtainable:

at an altitude of 1000 ft (300 m) — 50 n.m. (92 km)
at an altitude of 5000 ft (1500 m) — 92 n.m. (170 km)
at an altitude of 20,000 ft (6000 m)—182 n.m. (335 km)
at an altitude of 30,000 ft (9000 m)—220 n.m. (410 km)

The following reliable ranges were measured: 140 km (75 n.m.) at an

altitude of 3000 ft (900 m) or 170 km (95 n.m.) at an altitude of 5000 ft (1500 m).[10]

For aircraft operating at lower altitudes (helicopters, sports aircraft) the ranges will be reduced (at an altitude of 500 ft corresponding to 150 m approximately 60–70 km).

3.2. *Accuracy*

The overall error[5] comprises the following systematic errors:

ground station error,
airborne equipment error.

Each of these errors comprises:

equipment and antenna error,
site or location error resp.

The error curve of a VOR is established by orbit flights around the VOR and by comparing the azimuth indication to the nominal values (Annex 10, ICAO). It is of the semi-circular, quadrantal, sextant or irregular type with positive and negative deviations from the nominal value of the azimuth. With regard to the positive or negative maximum respectively, or with respect to the maximum error difference (difference between positive and negative maximum) certain limits are laid down.

The maximum error of the equipment including the antenna permitted by ICAO Annex 10 is $\pm 2°$ at a distance from the antenna of 4 times the wavelengths, and at an elevation of 0°–40°. The maximum ground station error (equipment, antenna and site error) should not exceed $\pm 3.5°$. The following empirical values of the maximum error are available:

Ground station: $\pm 1.58°$ (average of 25 ground stations)[9]

$\pm 2.5°$ [12]

$\pm 2.2°$ (average of eight ground stations, 20 measurements made within 3 years, 1956–58, of the same station after technical modifications only: maximum error of the poorest station $\pm 3.5°$, of the best station $\pm 0.8°$). BFS, Federal Republic of Germany.

$\pm 1.4°$ (average of 19 VORs, altogether 190 error contours; achieved by improvements in the aerial and ground checks). 1961, BFS, Federal Republic of Germany.

$\pm 2.0°$ (at 95 per cent probability, $\pm 3.5°$ at 99–97 per cent probability. The data of 276 VOR installations were processed by statistical methods. The error distribution complies with Gauss error distribution law).[19]

Airborne equipment (under normal operating conditions):

$\pm 0.75°$ Marconi receiver AD704[13]

$< \pm 1.2°$ Collins receiver 51R–2

$\pm 1.8°$ . . . 4.5°[12] without information of type*

$\pm 2.0°$ . . . 3.0° minor Narco and Lear receivers.

These errors can be kept constant and those owing to the ground station

* The airborne equipment error is dependent upon the maintenance of the equipment.

may be published with regard to distinguished directions (for instance, airways).

In case many VOR stations are in operation, it would be more reasonable to combine these errors with the second class of errors, the random errors, and thus to determine the error of the VOR system. This would also be recommendable with regard to the propagation errors which are for one part systematic errors (depending upon the very high frequency used) and for the other part random errors. In this connection the *en route* error should be particularly mentioned, which occurs due to reflections from hills, mountain ranges and lakes. This error occurs immediately in front or in the back of the interfering object and is indicated by relatively rapid deflections of the deviation indicator (" scalloping "). The interval between variations depends upon the course relative to the interference field. This should be distinguished from the error produced by reflecting objects in the vicinity of the VOR ground station, which appears as a bend of some kilometers in length in the line of position.[20] The amplitude of such scallopings may amount to $\pm$ 3–5° in mountainous country.[22]

The random errors comprise errors caused by:

variations of the supply voltage (ground and airborne equipment),
variations in the aerial, phase deviations of the r.f. partial fields,
variations of the r.f. power (propagation, reflections),
temperature changes,
receiver adjustment,
inaccurate reading.

The overall VOR system error (ground station and airborne equipment errors) as obtained by tests performed with commercial aircraft was[8]:

at 68 per cent of the tests $< \pm 1.7°$ (standard deviation)
at 95 per cent of the tests $< \pm 3.4°$
at 99.7 per cent of the tests $< \pm 5.1°$.

The total number of observations is not known. Other authorities[9] indicate an accuracy of the VOR system of:

$< \pm 4.8°$ at 99.7 per cent of the tests

These figures are based on 6355 observations. During these tests, which were also carried out with commercial aircraft, the direction indicated over known fixed ground points was compared with the true direction whereat high-quality airborne receivers were used. The maximum ground station error was $\pm$ 1.58° (average of 25 stations).

Recent investigations[21] showed an overall error of $\pm$ 1.54° when receivers of the highest quality class were used, and of 2.06° when receivers of a lower quality class were employed, the probability being 95 per cent in either case. The reduction in the error is due to improvements in the ground stations and their monitoring facilities (error of ground station $\pm$ 1.53° at a 95 per cent probability, as measured on 196 VORs; 1956: $\pm$ 2.15 per cent; 1954: $\pm$ 2.48° at 95 per cent) and to improvements in the airborne receiver. Since the standard deviation of 0.104° or 0.694° resp. of the two receiver categories under standard test conditions should be 0.5° or 1° resp. for all practical purposes, the overall error is $\pm$ 1.83° or 2.52° resp.

Thus all types of error, i.e. both systematic errors (ground and airborne equipment) and random errors, are treated by statistical methods, therefore

the overall error of the VOR system comprises the observation error of visual fixing.

3.3. *Ambiguity*

Indication is unambiguous when an omni-bearing indicator is used. When, however, an omni-bearing selector and deviation indicator is used, indication is ambiguous in that an opposite direction relative to the ground station results in equal measuring data and, hence, course data. This ambiguity is eliminated by the to/from indicator.

Two VORs operating on the same frequency should be spaced sufficiently far apart so that the zone of uncertainty caused by interference is sufficiently high above ground.

The geographical separation of VOR stations operating on the same frequency is indicated in the table of Add. 32, Annex 10 (ICAO) :

Selection	*S* (*dB/n.m.*)	*K* (*dB*)	*Minimum Geographical Separation Between Stations* (*n.m.*)
VOR_1—VOR_2	0.2	0	500
VOR_1—VOR_2	0.2	0	500
VOR_2—VOR_2	0.3	0	327
VOR_B—VOR_B	0.5	0	90
VOR_1—VOR_B	0.2	6	470
VOR_2—VOR_B	0.3	6	307

S = slope of the curve indicating the field strength-to-distance ratio for constant height (dB/n.m.).

K = power ratio of 2 VORs with equal or different nominal ranges.

VOR_1 and VOR_2 are of the same type (Type A VOR) but of different service ranges and a height utilization as follows :

VOR_1 200 n.m. 12,000 m (40,000 ft)

VOR_2 130 n.m. 6000 m (20,000 ft)

VOR_B an equipment of reduced power (Type B VOR) up to 25 n.m. 3000 m (10,000 ft)

4. NAVIGATIONAL AND OPERATIONAL CONSIDERATIONS

The pilot is provided with continuous course line information toward or away from the VOR station as line of position when an omni-bearing indicator is used, or with zero indication when an omni-bearing selector is used (cf. sections 1 and 2).

For establishing a fix either a distance measuring equipment (DME) or another line of position obtained from a second VOR is required. A period of approximately 2 min is required for establishing a fix. It is possible to employ computers and visual display which would eliminate the necessity of drawing the lines of position and thus simplify position fixing. Normally the airborne equipment is operated by the pilot without assistance. No special training is required.

For evaluation the following equipment is required:

table of VOR frequencies,

normal charts on which the VOR stations are indicated (no special charts are necessary).

The VOR system is suitable for coupling when the flight follows a radial line of position.

Maintenance of the airborne equipment is accomplished by the ground staff. The calibration of the equipment will have to be checked thoroughly and periodically. However, the operational reliability of the equipment is of a very high order. Commercial aircraft usually are equipped with two airborne installations. A VOR station can accommodate an unlimited number of users.

Since VOR ground stations are operating automatically, they do not require a permanently present staff; however, the equipment has to be checked periodically (weekly) by a radio engineer who is familiar with the equipment. The technical staff must be trained especially for their jobs in order to be able to work efficiently. The circuitry employed both in the ground station and in the airborne equipment is the commonly used one in modern v.h.f. techniques.

The operational reliability is in compliance with the technical and operational requirements. The equipment at present in use (dual equipment) meets the tolerance requirements at continuous day and night operation and under normal operating conditions without exceeding the maintenance expenditure mentioned above. (Frequency tolerance of the r.f. generator $\pm 5 \times 10^{-5}$, that of the 60-cycle generator $\pm 3 \times 10^{-3}$.)

The most sensitive part of the ground installation is the antenna insert containing the rotating dipole with drive and tone wheel whose service life hitherto has been 0.5 to 1 year (experience of the BFS). Other authorities claim a service life of several years.

In case of ground station failures automatic change-over to the standby transmitter results. For 50W TVORs a manually operated remote switch-over facility is provided at the control point of the airport. Observance of the zero phase angle in the direction of magnetic north is secured by regular maintenance.

As soon as the ground station does not operate within the determined tolerances, or the receiver input voltage falls below the permissible minimum value, flag alarm is given on the cross-pointer instrument.

Besides the normal navigational information an arbitrary adjustable identification signal is radiated without impairing the position-fixing procedure. Furthermore a voice communication channel is provided to transmit in the same manner both general or meteorological information periodically, e.g. automatically, or on request, without impairing the position-fixing procedure.

5. EXPENDITURE

5.1. *Ground Stations*

For the complete coverage of a larger area a suitable number of ground stations will have to be provided in compliance with ICAO regulations as mentioned in Sect. 3, para. 3. The existing and planned VOR station

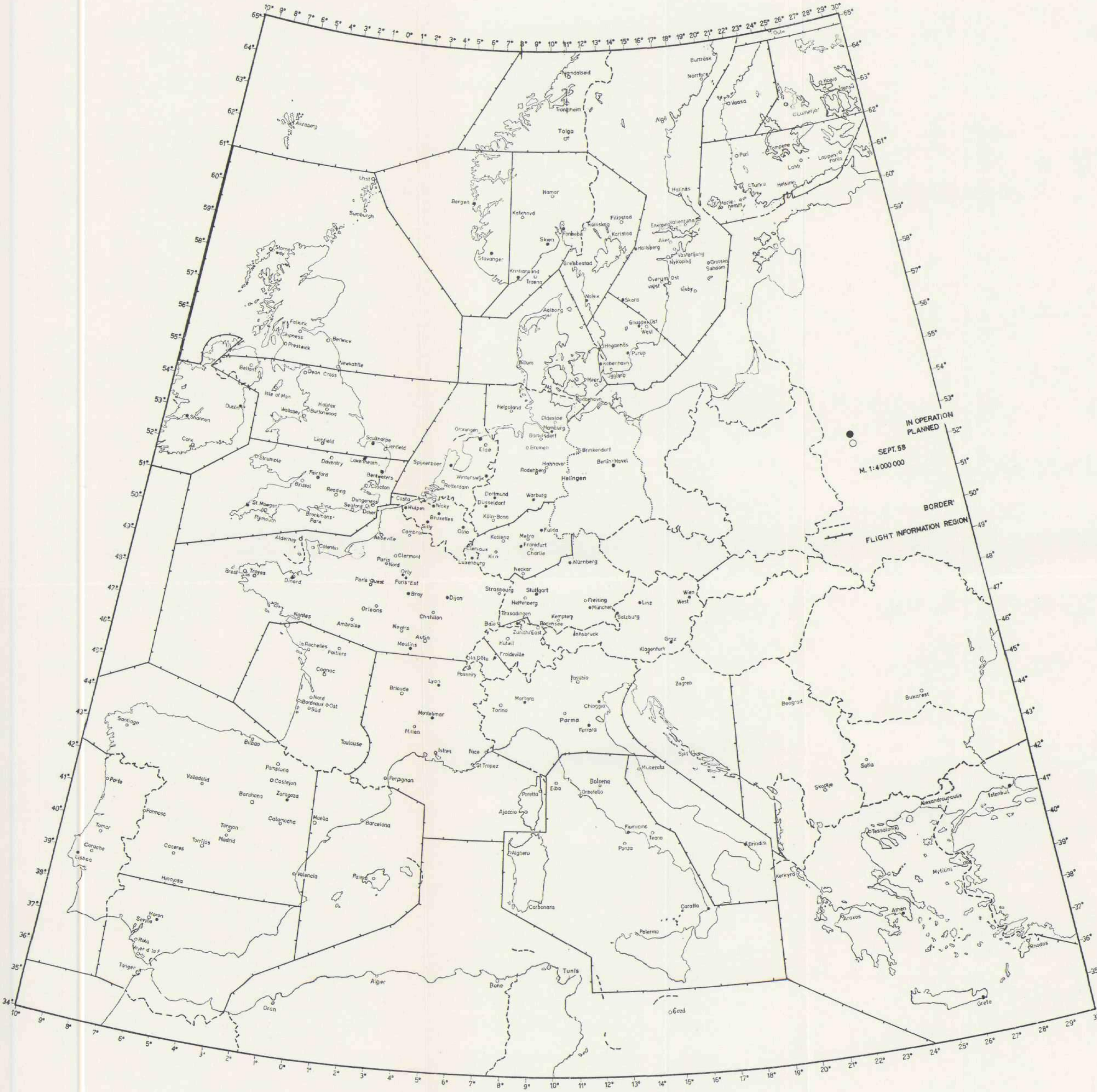

Fig. 4. Map of existing or planned VOR stations (Europe)

network is illustrated in Fig. 4 (EUM Frequency Coordinating Body Meeting (FCB), Paris, Sept. 1958).

5.1.1. *Technical data.* The ground stations are of two types:

normal VOR (200W),

installed load 7 kVA, and

low-powered VOR of 50W, designed for installation on an airport (TVOR), installed load 5 kVA.

The equipment is housed in a building of approximately 10 m diameter, on the roof of which the antenna is mounted.

5.1.2. *Dimensions and weights.* The dimensions and weights (including standby equipment) of a modern 200W station with cage antenna are:

Equipment	*Height (in.)*	*Width (in.)*	*Depth (in.)*	*Weight (lb)*
Four racks, complete	447	607	188	3750
Antenna	1400	227	227	77
Operator's station (remote control unit, desk set)	71	76	76	28,7
Tower box (terminal box for desk set)	173	109	109	112

A 50W station has only two racks (including standby equipment) since the racks of the power amplifiers are omitted. The weight is reduced accordingly.

5.1.3. *Prices.* The price of a 200W VOR station including assembly is approximately DM 140.000; that of the 50W station approximately DM 97.000. To this must be added the cost of approximately DM 60.000 for the VOR building including power supply installation. A similar station manufactured in the U.S.A. (with slotted antenna) including transmitter building of corrugated steel would cost in Germany DM 100.000 (200W) or DM 87.000 (50W) respectively.

5.1.4. *Terrain, siting and installation requirements, antenna.* A terrain of approximately 250 m² should be leased. No obstructions are allowed up to a distance of 65 m (300 ft) from the station. Only short cut grass may be tolerated in this area.

The siting requirements are outlined in Annex 10, ICAO. The station should be erected on the highest possible point to obtain the greatest line-of-sight coverage. The terrain should be level or should not slope away more than 4 per cent up to a distance of at least 300 m (1000 ft) or, better, 600 m (2000 ft) around the station, but in any case the site contours should be circular with respect to the antenna array to a radius of at least 300 m (1000 ft).

The height of wire lines or fences should not exceed a vertical angle of

1.5° relative to the ground or 0.5° relative to the antenna base. These values may be increased by a factor of 1.5 when the lines or fences are arranged radially to the antenna or subtend an azimuth angle of not more than 10°.

Single trees of normal extension and up to a height of 9 m (30 ft) are permissible beyond a distance of 150 m (500 ft) from the station. Groups of trees of a vertical angle of more than 2° are not permitted within 300 m (1000 ft) of the station. It is recommended to secure permission for clearing the terrain of trees up to 600 m (2000 ft) from the station.

Buildings should not be within a radius of 150 m (500 ft), beyond this distance, the vertical angle of solid buildings should not exceed 1.2°. For wooden structures of small horizontal extension with negligible metallic contents the permissible vertical angle may be increased up to 2.5°.

In mountainous terrain the station should be sited on top of the highest elevation and this should be flat or levelled to a radius of at least 45 m (150 ft).[13] In this case the antenna should be installed approximately ½ wavelength above ground in the centre of the graded area and the transmitter building should be erected outside this area at a sufficient distance to be below the optical line-of-sight. No trees, power lines, buildings, etc., should be present above the radio horizon between 45 m (150 ft) and 360 m (1200 ft) from the station. The access roads shall be kept in usable condition.

5.2. *Airborne Equipment*

5.2.1. *Technical data.* For reception normally a VOR–ILS receiver is used (cf. 2). The channels are separated by 100 kc/s at present. The bandwidth required for processing VOR signals is 21 kc/s.

Manufacturer	*Model*	*Sensitivity*	*Frequency Tolerance* (%)	*Power Input*	
				a.c. supply	*d.c. supply*
Marconi	AD 704	3 μV at 6 dB signal-to-noise ratio	± 0.0035	80 VA	
Bendix	MN–85	3 μV at 6 dB signal-to-noise ratio (200 mW output power)	± 0.01	100 VA	125 VA
Collins	51R–3	3μV at 6 dB signal-to-noise ratio (200 mW output power)	± 0.01	115 VA	100 W

The channel separation of other receivers is 50 kc/s (e.g. Collins 51R–4).

5.2.2. *Dimensions, Weights, Prices*

Collins receiver 51R–3 (all prices are listed).

Unit	*Weight* (*lb*)	*Dimensions* (*in.*)	*Price* (*US dollar*)
Receiver with shockmount	32.1	$24\frac{5}{6} \times 4\frac{1}{8} \times 7\frac{3}{4}$	2380
Antenna	5.75	—	200
Control unit	0.8	$3\frac{9}{16} \times 2\frac{1}{4} \times 2\frac{3}{16}$	100
Power supply	8.2	$7\frac{7}{32} \times 7\frac{1}{4} \times 5\frac{1}{8}$	168 from a.c. 208 from d.c.

Bendix receiver MN–85.

Unit	*Weight* (*lb*)	*Dimensions* (*in.*)	*Price* (*US Dollar*)
Receiver with shockmount	32.00	$26 \times 5.875 \times 9.23$	2440
Antenna	6.2	—	200
Control unit	1.1	$3.06 \times 2.75 \times 3.9$	128
Power supply	8.4	$9.57 \times 8.6 \times 5.6$	172 from a.c. 236 from d.c.

Instrumentation.

Unit	*Weight* (*lb*)	*Dimensions* (*in.*)	*Price* (*US—Dollar*)
Omni-bearing indicator	2.4	ϕ 3.125, depth 4.19	568
Omni-bearing selector	1.9	ϕ 3.125, depth 6.13	472.80
Deviation indicator	1.1	ϕ 3.156, depth 3.66	180
Radio-magnetic indicator	1.9	ϕ 3.125, depth 4.78	660

The price of a dual installation including instruments is approximately \$9500. (list price).

The weight of minor receivers is approximately 5 kg, their price is approximately \$2000, with simplified instrumentation (list price). Recently transistorized miniature receivers have been marketed.

5.2.3. *Installation requirements.* The receivers can be installed in the usual manner. The installation costs depend on the type of the aircraft, the weight and the costs of connecting cables on the location of the receiver. The airborne antenna (V dipole) should be located in the vertical plane of symmetry of the aircraft in order to secure a useful polar diagram. Normally it is installed on top of the fuselage.

6. FURTHER DEVELOPMENT (DOPPLER VOR)

VORs sometimes have to be installed on unfavourable sites. To reduce the errors which are due to reflecting objects in the vicinity of VORs (site

errors) the Doppler VOR was developed which allows the use of unaltered airborne equipment in spite of a different technology of the ground station.

The Doppler VOR station has a central aerial on a large metallic surface of 150 ft (45.75 m) in diameter and 50 single aerials arranged in a circle around the central aerial, with the circle diameter being 22 ft = approx. 6.7 m = approx. 2.5λ. The radiation pattern of each aerial is almost circular. The central aerial radiates the major portion of the r.f. energy which is amplitude-modulated with 30 c/s (first r.f. generator). This radiation component thus provides the reference phase in the airborne receiver. The 50 single aerials are energized individually by being fed consecutively with a frequency which is by 9960 c/s higher (second generator). Hence, for the purpose of explaining the principle, they may be replaced by a single rotating aerial. This fictitious source of radiation is rotated at a speed of 30 rev/sec. For this reason and because of the spacing (approximately 2.5λ) of the apparently rotating aerial, the radiation from this aerial (second r.f. generator), which is by 9960 c/s higher than that of the central aerial, is frequency modulated with a frequency deviation of ± 480 c/s. The phase of the 30 c/s modulation of this frequency-modulated oscillation (variable phase) depends directly on the directional angle of the receiver relative to the station. The airborne receiver thus receives a reference signal by screening the amplitude-modulated portion of the carrier frequency (central aerial) and a phase-variable signal by demodulation of the auxiliary carrier frequency of 9960 c/s which is frequency-modulated by 30 c/s.

Extensive studies were made of such installations in the U.S.A.[24] Under comparable site conditions the site errors or the bends respectively were reduced to one-quarter to one-seventh of their original magnitude for most bearings (e.g. Charleston VOR from ± 2.8°–0.4°). The theory behind this system including also the error theory are contained in refs. 25 and 26.

The technical requirements of a Doppler VOR, especially for the aerial system, are considerably greater than those for a conventional VOR. Also a larger area is required. The environmental requirements (protective zones) are reduced. The system is not yet commercially available. Hence, no prices can be given.

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